CAN WE LEARN SOMETHING MORE ON OSCILLATIONS FROM ATMOSPHERIC NEUTRINOS?

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We show that for long-baseline experiments using a Mt water Čerenkov detector atmospheric neutrino data provide a powerful method to resolve parameter degeneracies. In particular, the combination of long-baseline and atmospheric data increases significantly the sensitivity to the neutrino mass hierarchy and the octant of θ_{23}. Furthermore, we discuss the possibility to use μ-like atmospheric neutrino data from a big magnetized iron calorimeter to determine the neutrino mass hierarchy.

1. Introduction

In the past atmospheric neutrinos have played an important role in establishing the phenomenon of neutrino oscillations[1]. However, now we are entering the era of high precision long-baseline (LBL) experiments[2,3,4,5] which will outperform atmospheric neutrinos in the determination of the oscillation parameters $|\Delta m_{31}^2|$ and $\sin^2 2\theta_{23}$. Hence, the question raised in the title of this talk arises. In the following I will suggest that the answer to this question is "yes", by discussing possibilities to use atmospheric neutrino data from Mt scale water Čerenkov detectors[6] or from large magnetized iron calorimeters[7] (see also Ref.[8] for a recent review).

2. Combining LBL and ATM data from Mt water detectors

The primary aims of future neutrino experiments are the determination of the mixing angle θ_{13}, the CP-phase δ_{CP}, and the type of the neutrino mass hierarchy (normal or inverted), i.e., the sign of Δm_{31}^2. It is well known that parameter degeneracies are a severe problem on the way towards these goals. In Ref.[9] it was demonstrated that for LBL experiments based on Mt scale water Čerenkov detectors data from atmospheric neutrinos (ATM) provide an attractive method to resolve degeneracies.

Atmospheric neutrinos are sensitive to the neutrino mass hierarchy if θ_{13} is sufficiently large due to Earth matter effects, mainly in multi-GeV e-like events[10]. Moreover, sub-GeV e-like events provide sensitivity to the octant of θ_{23}[11,12] due to oscillations with Δm_{21}^2. However, these effects can be explored efficiently only if LBL data provide a very precise determination of $|\Delta m_{31}^2|$ and $\sin^2 2\theta_{23}$, as well as some information on θ_{13}[9].

Here we illustrate the synergies from a combined LBL+ATM analysis at the examples of the T2K phase II experiment[3] (T2HK) with the HK detector of 450 kt fiducial mass, and two experiments with beams from CERN to a 450 kt detector at Frejus (MEMPHYS)[5], namely the SPL super beam and a $\gamma = 100$ beta beam (βB). The LBL experiments are simulated with the GLoBES software[13], and a general three-flavor analysis of ATM data is performed[5,9,12]. For each experiment we assume a running time of 10 years, where the neutrino/anti-neutrino time is chosen as 2+8 years for SPL and T2K, and 5+5 years for the beta beam, see Ref.[5] for details.

The effect of degeneracies becomes apparent in Fig. 1. For given true parameter values the data can be fitted with the wrong hierarchy and/or with the wrong octant of
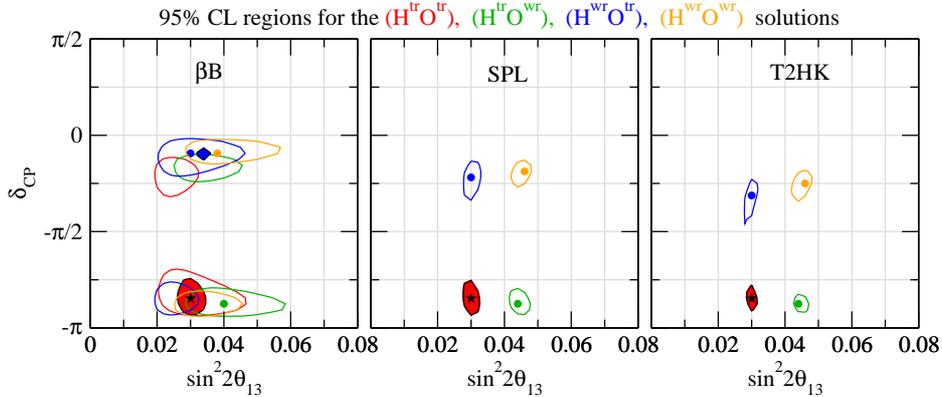
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Fig. 1.   Allowed regions in $\sin^2 2\theta_{13}$ and $\delta_{\rm CP}$ for LBL data alone (contour lines) and LBL+ATM data combined (colored regions). The true parameter values are $\delta_{\rm CP} = -0.85\pi$, $\sin^2 2\theta_{13} = 0.03$, $\sin^2 \theta_{23} = 0.6$. $\mathrm{H^{tr/wr}(O^{tr/wr})}$ refers to solutions with the true/wrong mass hierarchy (octant of θ_{23}).

θ_{23}. Hence, from LBL data alone the hierarchy and the octant cannot be determined. Moreover, as visible from the solid lines in Fig. 1 the degenerate solutions appear at parameter values different from the true ones, an hence, ambiguities exist in the determination of θ_{13} and $\delta_{\rm CP}$. If the LBL data are combined with ATM data only the colored regions in Fig. 1 survive, i.e., in this particular example for all three experiments the degeneracies are completely lifted at 95% CL, the mass hierarchy and the octant of θ_{23} can be identified, and the ambiguities in θ_{13} and $\delta_{\rm CP}$ are resolved. Let us note that here we have chosen a favorable value of $\sin^2 \theta_{23} = 0.6$; for values $\sin^2 \theta_{23} < 0.5$ in general the sensitivity of ATM data is weaker[9].

In Fig. 2 we show the sensitivity to the neutrino mass hierarchy. For LBL data alone there is practically no sensitivity for the CERN–MEMPHYS experiments (because of the very small matter effects due to the relatively short baseline of 130 km), and the sensitivity of T2HK depends strongly on the true value of $\delta_{\rm CP}$. However, with the LBL+ATM combination all experiments can identify the mass hierarchy at 2σ CL provided $\sin^2 2\theta_{13} \gtrsim 0.02 - 0.03$ [5].

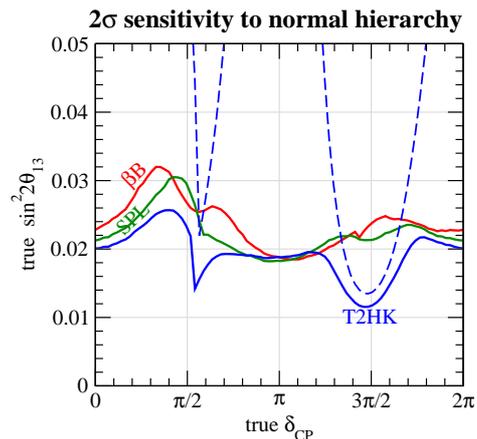Fig. 3 shows the potential of ATM+LBL data to exclude the octant degenerate solu-

Fig. 2.   Sensitivity to the neutrino mass hierarchy as a function of $\sin^2 2\theta_{13}$ and $\delta_{\rm CP}$ for $\theta_{23}^{\rm true} = \pi/4$ and a true normal hierarchy. Solid curves correspond to LBL+ATM data combined, the dashed curves correspond to T2HK LBL data-only. βB and SPL without ATM have no sensitivity to the hierarchy.

tion. Since this effect is based mainly on oscillations with Δm_{21}^2 there is very good sensitivity even for $\theta_{13} = 0$; a finite value of θ_{13} in general improves the sensitivity[9]. From the figure one can read off that atmospheric data alone can resolve the correct octant at 3σ if $|\sin^2 \theta_{23} - 0.5| \gtrsim 0.085$. If atmospheric data is combined with the LBL data from SPL or T2HK there is sensitivity to the octant for $|\sin^2 \theta_{23} - 0.5| \gtrsim 0.05$.
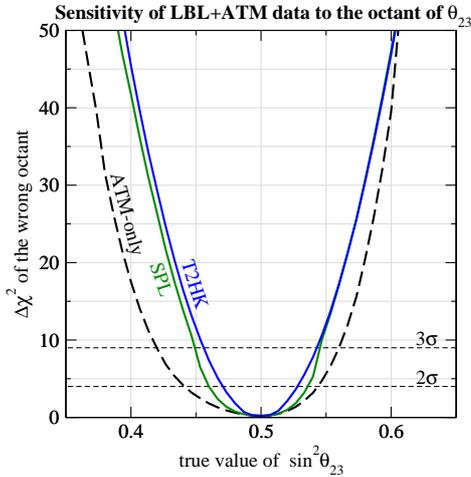
Fig. 3. $\Delta\chi^2$ of the solution with the wrong octant of θ_{23} as a function of $\sin^2\theta_{23}$. We have assumed a true value of $\theta_{13} = 0$.

3. Magnetized iron calorimeters

In water Čerenkov detectors one cannot distinguish between neutrino and anti-neutrino events. This limits the sensitivity to the mass hierarchy, since depending on the hierarchy the resonance occurs either for neutrinos or anti-neutrinos. Therefore, in principle one expects that the sensitivity improves for detectors capable to distinguish atmospheric neutrino from anti-neutrino events. In the following we discuss the possibility offered by a large (several 10 kt) magnetized iron calorimeter similar to the INO proposal[7]. Such a detector can determine the charge of muons, whereas electron detection is difficult. The principles of atmospheric neutrino measurements with a 5.4 kt detector of this type have been established recently by the MINOS experiment[14].

Here we report the results obtained in Ref.[15], see Ref.[16] for related considerations. We limit ourselves to μ-like events, and we assume a correct identification of ν_μ- versus $\bar\nu_\mu$-events of 95%. The observation of the muon and the hadronic event allows in principle to reconstruct the original direction and energy of the neutrino. Indeed, it has been stressed in Ref.[15] that the accuracy of neutrino energy and direction reconstruction is crucial for the determination of the hierarchy. The reason is that the difference in the event spectra of normal and inverted hierarchy show a characteristic oscillatory pattern. If this pattern can be resolved a powerful discrimination between the hierarchies is possible. If however, the oscillatory pattern is washed out because of a poor accuracy in energy and direction reconstruction the sensitivity to the hierarchy decreases drastically.

In Fig. 4 we show the sensitivity to the hierarchy for a 500 kt yr exposure of an INO-like detector. In the left panel we assume that the neutrino energy can be reconstructed with an accuracy of 15% and the neutrino direction with an accuracy of $15°$, whereas in the right panel the very optimistic accuracies of 5% and $5°$ are adopted. Details on our simulation and systematic errors are given in Ref.[15]. One observes from the plot that for optimistic assumptions the hierarchy can be identified at 2σ if $\sin^2 2\theta_{13} \gtrsim 0.02$. This sensitivity is comparable to the one from Mt water Čerenkov detectors discussed in the previous section. If however, more realistic values for the energy and direction reconstruction are adopted the sensitivity deteriorates drastically and values of $\sin^2 2\theta_{13} \gtrsim 0.1$ (close to the present bound) are required.

4. Conclusions

In this talk I have discussed the potential of future atmospheric neutrino experiments. An interesting possibility arises if a LBL super beam or beta beam experiment with a Mt scale water Čerenkov detector is built. In such a case the high statistics atmospheric neutrino data available in the detector may provide complementary information to the LBL data and help to resolve parameter degeneracies. In particular, the sensitivity to the neutrino mass hierarchy and the octant

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solid: true hierarchy normal,   **dashed:** true hierarchy inverted
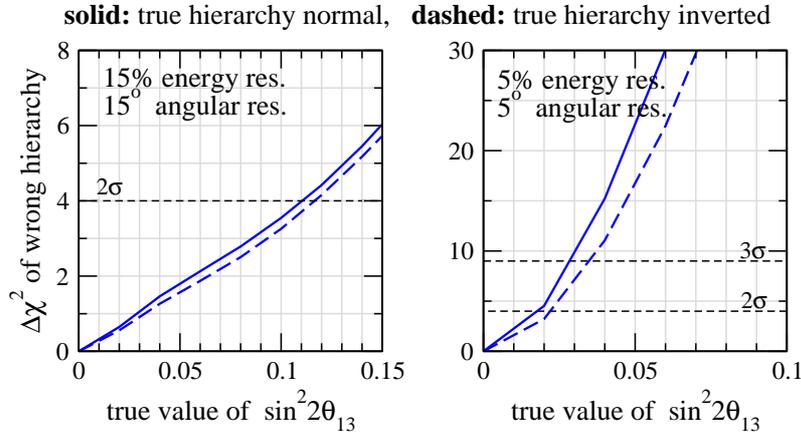

Fig. 4.   Sensitivity to the neutrino mass hierarchy of a magnetized iron calorimeter for different assumptions on the neutrino energy and direction reconstruction accuracy. We assume 500 kt yr data from an INO-like detector, corresponding to 4000 up-going μ-like events with $E_\mu > 2$ GeV. Here, $\theta_{23}^{\text{true}} = \pi/4$ and we assume external information on $|\Delta m_{31}^2|$ and $\sin^2 2\theta_{23}$ of 10%, and an uncertainty on $\sin^2 2\theta_{13}$ of ± 0.02.

of θ_{23} is significantly increased. Furthermore, I have discussed large magnetized iron calorimeter detectors. Such detectors are under consideration as far detector for a neutrino factory, and can be viewed as an upscaled version of the present MINOS experiment. For the determination of the neutrino mass hierarchy with μ-like events in a magnetized iron detector the ability to reconstruct the neutrino energy and direction with good accuracy is crucial.

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